

CALIPSO'S MISSION DESIGN: SUN-GLINT AVOIDANCE STRATEGIES

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CALIPSO will fly in formation with the Aqua spacecraft to obtain a coincident image of a portion of the Aqua/MODIS swath. Since MODIS pixels suffering sun-glnt degradation are not processed, it is essential that CALIPSO only co-image the glint free portion of the MODIS instrument swath. This paper presents sun-glnt avoidance strategies for the CALIPSO mission. First, we introduce the Aqua sun-glnt geometry and its relation to the CALIPSO-Aqua formation flying parameters. Then, we detail our implementation of the computation and perform a cross-track trade-space analysis. Finally, we analyze the impact of the sun-glnt avoidance strategy on the spacecraft power and delta-V budget over the mission lifetime.

INTRODUCTION

The Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) mission is jointly developed under partnership by NASA Langley Research Center (LaRC), the French Centre National D'Etudes Spatiales (CNES), Hampton University (HU), the Institute Pierre Simon Laplace (IPSL), and Ball Aerospace. The goal of the CALIPSO mission is to provide measurements of aerosols, cloud vertical structure and cloud optical properties. CALIPSO is a member of the Afternoon Constellation along with the Aqua, CloudSat, Parosol and Aura satellites.¹⁻³ To meet its science objective, the CALIPSO spacecraft will fly in formation with the Aqua spacecraft in a frozen, Sun-synchronous orbit with a 705-kilometer altitude at the equator crossing. The CALIPSO mission, currently planned to be launched in March 2005, is divided in two phases with a total mission lifetime of 3 years.⁴⁻⁶ During the first two years of the mission, referred to as Phase 1, CALIPSO will closely follow Aqua so that its CALIOP (Cloud-Aerosol LIDar with Orthogonal Polarization) instrument takes measurement of a small portion of the Aqua MODIS (MODerate resolution Imaging Spectro-radiometer) instrument's imaging swath at the ascending node crossing. During the last year of the CALIPSO mission, referred to as Phase 2, CALIPSO's orbit will precess to enable the CALIOP instrument to sample the western section of Aqua's MODIS instrument swath.

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NASA's Terra mission, launched in 1999, is flying a MODIS instrument performing measurements identical to the Aqua's. Scientists discovered that Terra MODIS image data are degraded by sun-glint, since the MODIS is unable to distinguish sun-glint from highly reflective clouds. Based on the results of the Terra MODIS instrument data, the Aqua imaging strategy was modified so that its MODIS does not process data that are within a predefined sun-glint region. This change in imaging strategy led the CALIPSO science team to reconsider their formation flying strategy with Aqua during Phase 1.^{7,8} The original CALIPSO strategy was to fly in formation with Aqua such that CALIOP observed the that portion of the MODIS swath covering Aqua's sub-satellite point (i.e. the point on the Earth directly along Aqua's nadir direction) within 2 minutes of Aqua's measurements. Because the data loss due to the sub-satellite point passage through the sun-glint region was judged to be unacceptable, a change in the way CALIPSO flies in formation with Aqua during Phase 1 was considered. If CALIPSO could fly behind Aqua with an eastern cross-track shift with respect to Aqua's sub-satellite point, then CALIPSO could perform its coincident imaging with a portion of the MODIS swath that is affected less by sun-glint (see Figure 1 for the relevant geometry). Its time separation strategy with Aqua would remain identical to the original plan to eliminate any close approach issues and to ensure that the coincident imaging conditions are met.

This paper is divided into four sections. The first section presents the Aqua MODIS sun-glint geometry and its relationship to the CALIPSO-Aqua formation flying geometry. The second section details the implementation of the sun-glint computation for Phase 1 of the CALIPSO mission. The third section discusses the results from the cross-track trade-space analysis as well as the impact of the cross-track error budget on CALIPSO's imaging strategy. Finally, the fourth section focuses on the impact of the sun-glint avoidance strategy on the spacecraft power and delta-V budget over the mission lifetime.

THE SUN-GLINT AND FORMATION FLYING GEOMETRIES

In this section, a definition of sun-glint and a brief description of the corresponding Sun-Earth-CALIPSO orbit geometry are provided. Then, a more detailed derivation of the Aqua MODIS-specific sun-glint geometry with its appropriate frame and variables are given. Finally, the main formation-flying design parameters are presented in relation to the sun-glint geometry.

Sun-glint Definition

Sun-glint is created by the reflectance of high-intensity solar rays from the Earth's surface. The closer the reflected rays are to the specular direction, the higher is their intensity. High-intensity reflected rays can prevent the MODIS instrument from performing proper science measurements; this phenomenon was observed on the Terra mission. Based on the Terra findings, Aqua does not process any data suffering from sun-glint, defined to be data collected within 40° of the specular direction. Because of power considerations, the CALIPSO team chose to mitigate data loss originating within a 35° cone about the specular direction.

Figure 1 shows a schematic of the Aqua sun-glint region, shown on a 2-D projection in the Earth's body-fixed frame, looking down the nadir with respect to the MODIS swath for October 01, 2001. Because the sun-glint region is determined by the Sun-Earth-Aqua orbit geometry, its position with respect to the MODIS swath will vary with the seasons. The relative Sun path, as seen on the 2-D projection on the Earth's, is called the analema⁹ and is shown in Figure 2. The Sun traces a figure-eight ground track on the Earth, where the highest latitude point represents

the summer solstice and the lowest latitude the winter solstice. The equator crossing point represents the spring and fall equinoxes. The sun-glint region moves as the Sun moves along the analema.

Another interesting parameter for this study is the beta angle defined as the complement to the angle between the normal to the orbit plane and the Sun. In other words, it represents the angle between the orbital plane and the Sun as illustrated in Figure 3. The smaller the beta angle is the closer is the Sun to shining onto the edge of the spacecraft's orbit plane. The worst sun-glint case will occur at the smallest beta angle. Figure 4 shows Aqua's beta angle history for one year. From Figure 4, it can be observed that the worst case occurs around summer solstice.

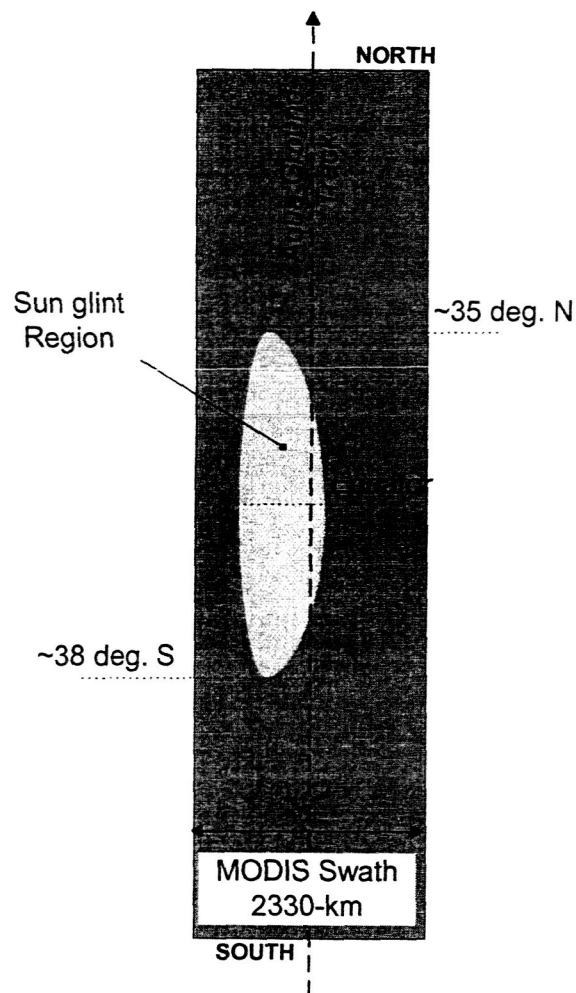


Figure 1. Aqua MODIS Sun-glint Region Schematic for One Revolution (Epoch: October 01, 2001).

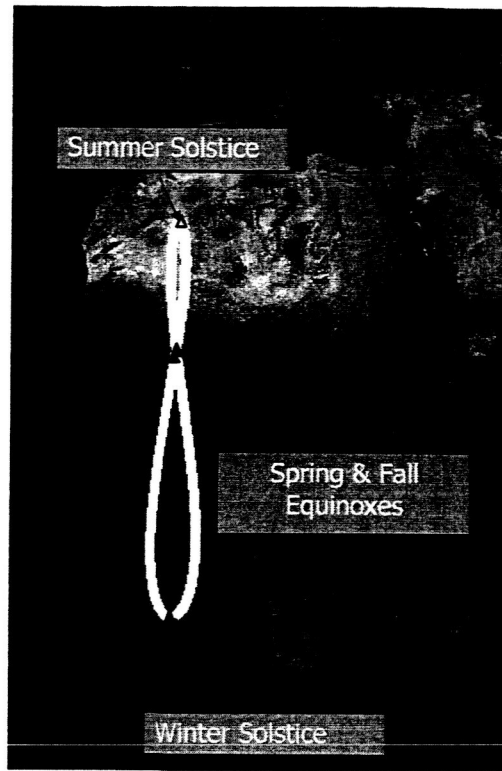


Figure 2. Sun Analema for 1 year (Starting Epoch June 21, 2004 12:00:00.000)

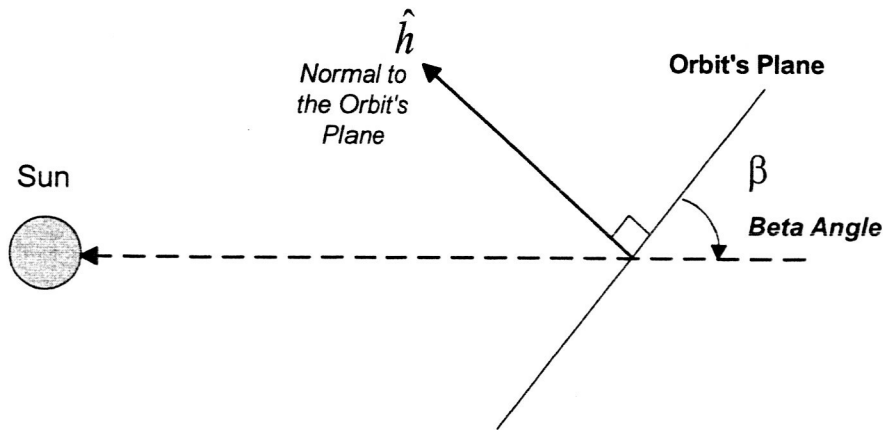


Figure 3. Schematic of the Beta Angle Definition

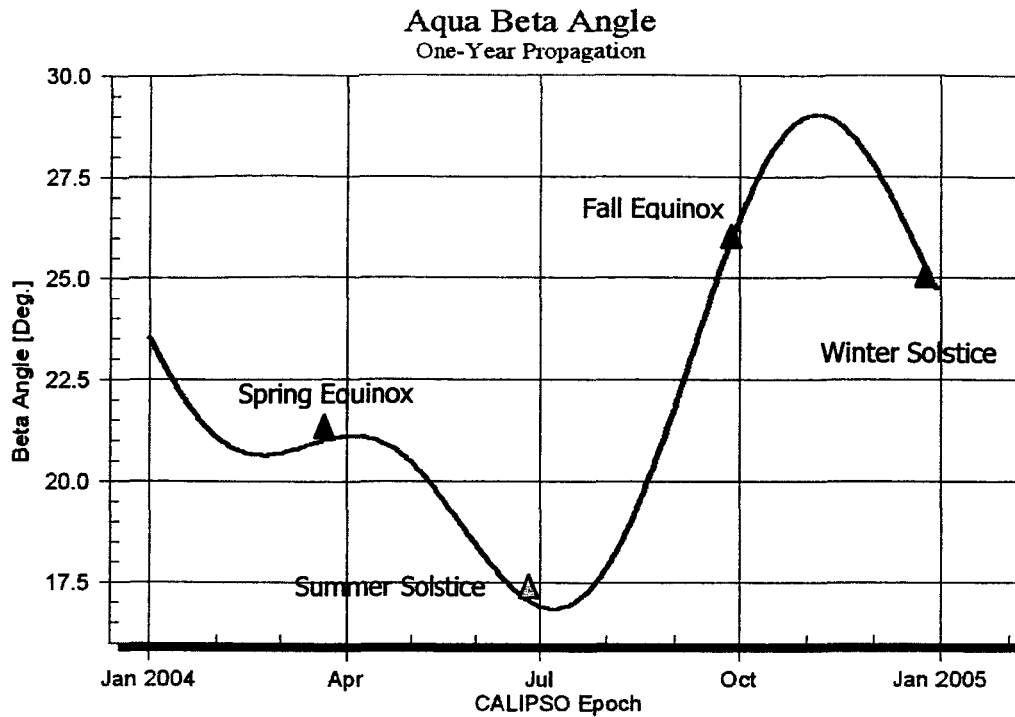


Figure 4. Aqua's Beta Angle for One-Year Propagation

Aqua Sun-glint Geometry

To derive quantitative results, a detailed model of the Aqua sun-glint imaging is needed. The Aqua MODIS swath was divided into 33286 pixels, each pixel being 70 meters in size which corresponds to the diameter of the CALIOP swath. The aim is then to determine whether a given pixel (labeled P) of the Aqua's MODIS instrument is suffering from sun-glint or not.

The first vector of interest is the Sun-Earth unit vector in the mean of J2000 Geocentric Inertial (GCI) frame for a specific epoch, labeled $\hat{\gamma}$, which is defined as:

$$\hat{\gamma} = \frac{\overline{ES}}{\|ES\|} \quad (1)$$

where E and S represent the Earth and the Sun, respectively.

Let us assume that the angle between Aqua's nadir direction and the vector from Aqua to the MODIS pixel P is known. This angle is referred to as the view angle or MODIS angle (θ_v). Figure 5 illustrates a schematic of the MODIS sensor view angle geometry as defined for a given pixel P.

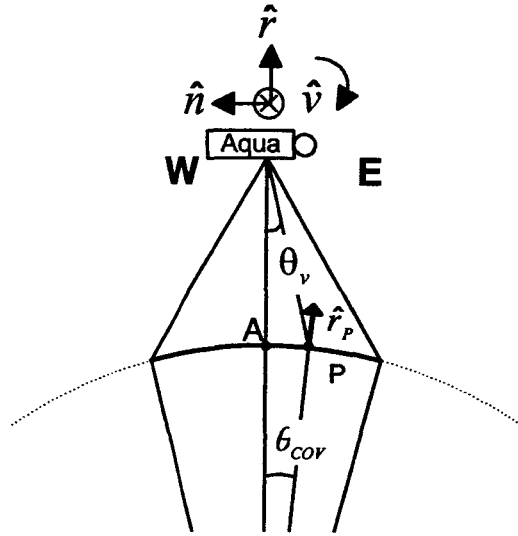


Figure 5. A Schematic of the MODIS Sensor View Angle Geometry for a Given Pixel P

The coverage angle (θ_{cov}) is defined as the angle between the Aqua sub-satellite point (labeled A in Figure 5) and a given pixel P with respect to the Earth's center. From the view angle (θ_v), the coverage angle can be derived by solving the implicit function shown below:

$$f(\theta_{cov}) = 0 = \tan(\theta_v) - \frac{r_e \cdot \sin(\theta_{cov})}{h + r_e \cdot (1 - \cos(\theta_{cov}))} \quad (2)$$

where h represents Aqua's height in km and r_e is the Earth mean radius in km.

Knowing the coverage angle, the radial direction at P (\hat{r}_p) can be expressed in terms of Aqua's radial (\hat{r}) and normal unit (\hat{n}) vectors as shown in Eq. (3).

$$\hat{r}_p = \sin(\theta_{cov}) \cdot \hat{n} + \cos(\theta_{cov}) \cdot \hat{r} \quad (3)$$

With Aqua's MODIS sensor viewing geometry defined, the complete sun-glnt geometry can be specified. Using Eqs. (1) and (3), the reflected Sun ray direction $\hat{\gamma}_R$ can be computed for a given P. The angle between the incoming ray and the radial direction at P, referred to as Sun zenith angle (θ_z), is expressed as:

$$\theta_z = \cos^{-1}(\hat{r}_p \cdot \hat{\gamma}) \quad (4)$$

The reflected Sun ray direction is then obtained by rotating the incoming ray vector about the normal to the plane ($\hat{\gamma}$, \hat{r}_p) by $2 \cdot \theta_z$:

$$\hat{\gamma}_R = \cos(2 \cdot \theta_z) \cdot \hat{\gamma} - \sin(2 \cdot \theta_z) \cdot \hat{c}_R \quad (5)$$

where

$$\hat{c}_R = \hat{n}_R \times \hat{\gamma} \quad (6)$$

and

$$\hat{n}_R = \frac{(\hat{r}_p \times \hat{\gamma})}{\|\hat{r}_p \times \hat{\gamma}\|} \quad (7)$$

The sun-glnt angle (θ_G) for pixel P is defined as the angle between the reflected ray vector and the direction from the pixel P to Aqua, also referred to as view vector:

$$\theta_G = \cos^{-1}(\hat{\gamma}_R \bullet \hat{V}_{view}) \quad (8)$$

where

$$\hat{V}_{view} = \frac{\hat{r} - \hat{r}_p}{\|\hat{r} - \hat{r}_p\|} \quad (9)$$

If, for a given pixel P, the value of the glint angle goes below the critical value of 35° at any given time during the mission, we will say that the pixel measurement suffers from sun-glnt and coincident imaging between CALIPSO and Aqua will be deemed impossible.

Formation Flying Geometry

Now that we can assess whether a given Aqua MODIS pixel suffers from sun-glnt or not, we can design the CALIPSO formation flying with Aqua in order to avoid coincident CALIOP imaging with the Aqua sun-glnt region. The CALIPSO's formation flying strategy requires two parameters to be specified: CALIPSO's equator crossing lag time with respect to Aqua (dt_{lag}) and the desired eastern cross-track shift ($shift_{glnt}$) at equator crossing with respect to the Aqua MODIS swath. The lag time will be held constant throughout this analysis at a nominal value of 1.22 minutes. This nominal value is derived from Aqua's and CALIPSO's respective control box sizes. In the initial formation flying strategy, CALIPSO was to fly directly behind Aqua so that CALIOP could image the Aqua sub-satellite point (i.e., zero view angle and zero $shift_{glnt}$).^{4,6} For the sun-glnt avoidance formation flying strategy, CALIPSO's orbit is shifted east with respect to the Aqua spacecraft's orbit; the magnitude of the cross-track shift can be varied to enable coincident imaging with a portion of the MODIS swath not suffering from sun-glnt. Figure 6 summarizes the Aqua sun-glnt geometry as defined in this paper in relation to the CALIOP instrument beam.

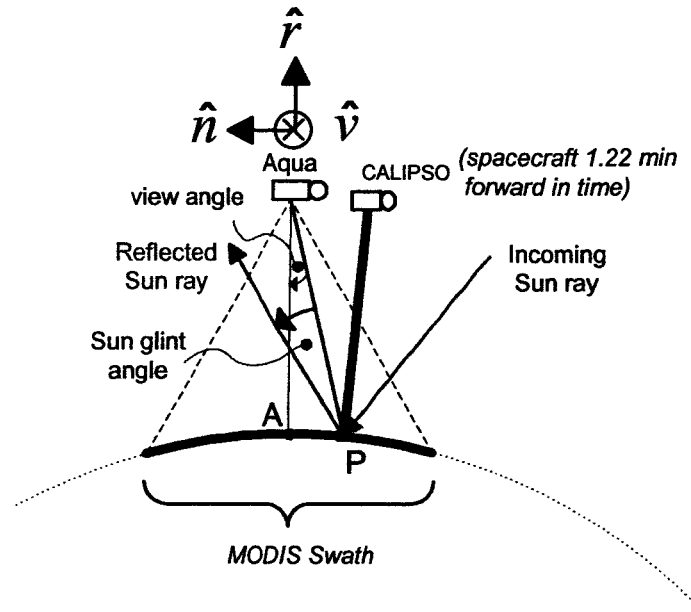


Figure 6. Schematic of the Sun-glint Geometry

The cross-track shift will be varied and the glint angle and view angle computed for each different cross-track value. Note that the right ascension of the ascending node includes an additional shift to compensate for the rotation of the Earth during dt_{lag} . Thus, when propagated forward 1.22 minutes, CALIPSO will “see” the same MODIS pixel on the ground as specified by $shift_{glint}$. Based on the two formation flying design parameters, the CALIPSO initial conditions are determined. Then Eqs. (10) and (11) are used as approximations to estimate CALIPSO’s initial true anomaly (TA) and right ascension of the ascending node (Ω).

$$TA_{CALIPSO} = TA_{Aqua} - \frac{360}{P_{Aqua}} \cdot dt_{lag} \quad (10)$$

$$\Omega_{CALIPSO} = \Omega_{Aqua} + \frac{360}{d2m} \cdot dt_{lag} + Shift_{glint} \quad (11)$$

where $d2m$ is a day expressed in minutes (i.e., 1440 minutes) and P_{Aqua} is Aqua’s period. Note that $Shift_{glint}$ is the plane shift due to sun-glint avoidance strategy only.

The sun-glint angle computation described in this section will be implemented for various CALIPSO formation flying strategies. A more detailed explanation about the control strategy is given in the last section of this paper.

SUN GLINT COMPUTATION IMPLEMENTATION

In the previous section, an expression computing the sun-glint angle for a given view angle (or cross-track shift) was given. While an approximation to the sun-glint angle and desired formation flying parameters can be generated using spherical geometry and two-body motion,¹⁰ we choose to implement the above equations in conjunction with high-fidelity models of the

formation's orbital motion in a FreeFlyer®/MATLAB® simulation. The CALIPSO FreeFlyer® script is fully automated and it allows quick and easy runs of the sun-glint angle trade-space analysis to be performed.

For our simulation, Aqua's trajectory was modeled using the latest Aqua mission planning ephemeris. The Aqua spacecraft state was propagated to the desired starting epoch. A graphical user panel prompts the user to enter the desired cross-track $shift_{glint}$ range, a step value for variation in a for-loop and dt_{lag} (set to 1.22 minute for this study) for the trade-space analysis. The formation flying cross-track parameter $shift_{glint}$ is varied via a for-loop. Based on Aqua's state and the formation flying parameters, CALIPSO's new formation flying initial conditions are determined using the FreeFlyer® targeter with Eqs.(10) and (11) as initial guesses. The targeter tolerances were set to ± 0.0001 minute and ± 0.5 km for the dt_{lag} and $shift_{glint}$, respectively. The CALIPSO spacecraft force model was set to be identical to the one used to generate Aqua's ephemeris. For each $shift_{glint}$ cross-track value, CALIPSO and Aqua's orbits are propagated for one revolution, during which the Sun zenith angle, the MODIS pixel view angle and the sun-glint are computed using MATLAB®. For this simulation, the view angle corresponding to a given cross-track shift is computed using a fictitious spacecraft (labeled CP_View) as shown in Figure 7.

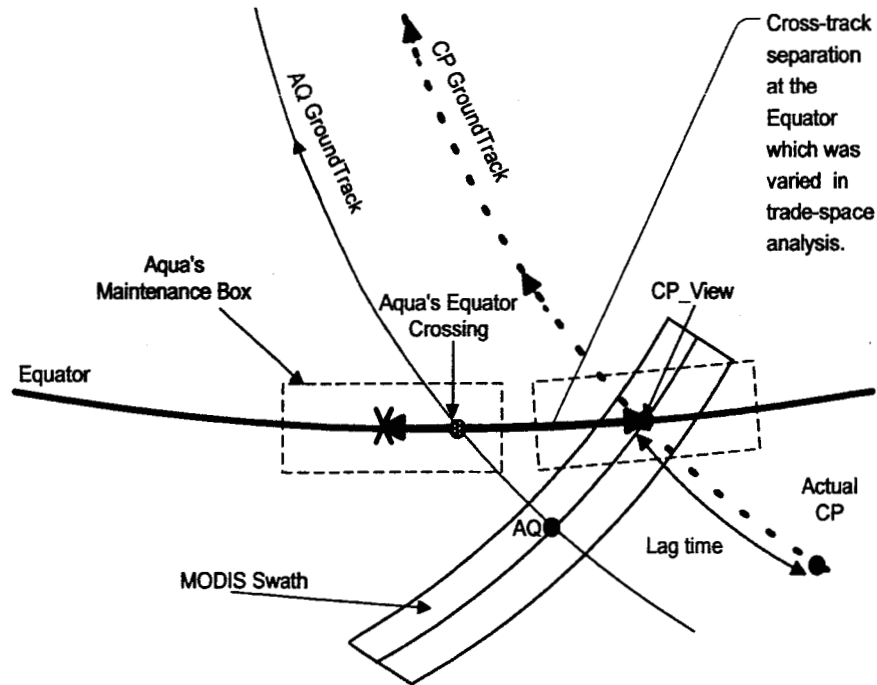


Figure 7. Schematic of Fictitious Spacecraft (CP_View) Geometry

The fictitious spacecraft's trajectory is designed such that it flies directly above the Aqua's MODIS swath, crossing the equator at the same time as Aqua (i.e., zero lag time). Its ground-track is identical to the actual CALIPSO ground-track (labeled CP). The view angle computations are directly derived from CP_View as shown in the equations below:

$$\theta_{Cov} = \cos^{-1} \left(\frac{\bar{r} \cdot \bar{r}_p}{\|\bar{r}\| \|\bar{r}_p\|} \right) \quad (12)$$

$$\theta_v = \cos^{-1} \left(\frac{-\bar{r} \cdot \bar{r}_{AP}}{\|\bar{r}\| \|\bar{r}_{AP}\|} \right) \quad (13)$$

where \bar{r} is Aqua's position vector and \bar{r}_p is CALIPSO's position vector when co-imaging a portion of the MODIS swath (i.e., CP_View position vector).

TRADE-SPACE ANALYSIS RESULTS

In the previous section, we presented our implementation of the sun-glnt angle for a given cross-track (or view angle). In this section, we run a trade-space analysis with cross-track shift values with respect to Aqua equator crossing varied from 0 to 260 km in steps of 10 km. If at a given epoch, a chosen pixel (characterized here by its maximum view angle) does not suffer from sun-glnt then it is also true for all epochs with beta angle greater than the considered epoch. Following that logic, the cross-track separation value should be based on the summer solstice epoch as it is close to the minimum beta angle value. For each cross-track shift value, we computed the corresponding view angle and glnt angle. Once we found the minimum cross-track shift which ensures co-imaging with a glnt free portion of the Aqua MODIS, we refined our solution to within 1 km accuracy.¹¹ Note that a 10 km east cross-track shift at the Equator crossing translates into a change in right ascension of ascending node of 0.089849°. Figure 8 shows the Sun zenith angle evolution for one orbit at Aqua's sub-satellite point for the summer solstice (i.e., the worst sun-glnt case). When the Sun zenith angle is greater than 90°, Aqua has crossed to the 'night-side' of the Earth where the measurements are not affected by sun-glnt and can be neglected from this study. All subsequent plots do not include the 'night-side' portion of Aqua's ground-track. Figure 9 represents the view angle evolution as a function of latitude. As expected, the maximum view angle is reached around the Equator crossing. For the chosen $shift_{glnt}$ coarse range, the maximum view angle ranges from 0° to 22° in steps of about 0.8°. Figure 10 shows the sun-glnt angle history as a function of latitude. The 35° threshold is indicated by a thick horizontal line to highlight which cross-track cases were suffering from sun-glnt.

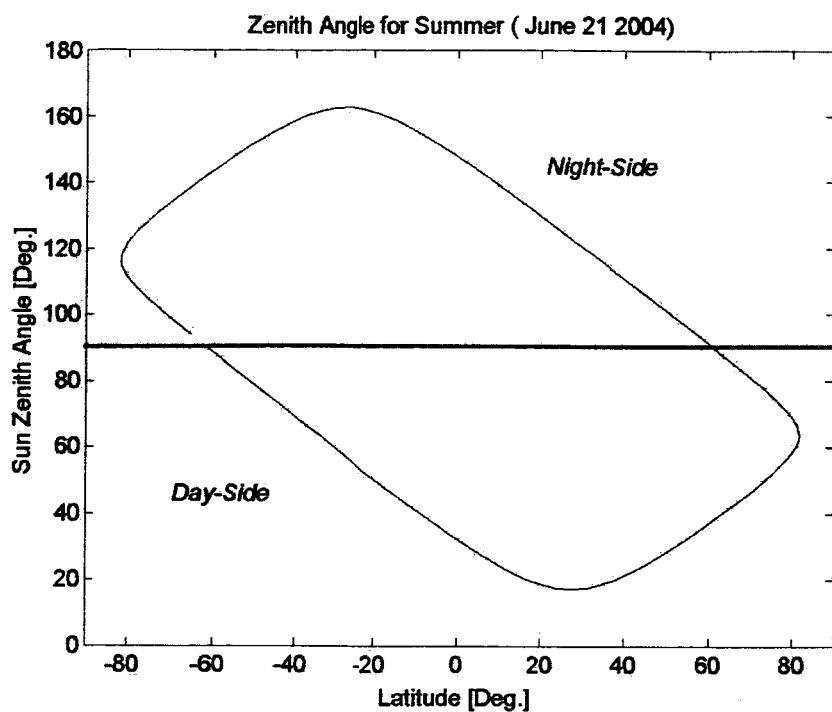


Figure 8. Sun Zenith Angle for Aqua's Sub-Satellite Pixel versus Latitude at the Summer Solstice

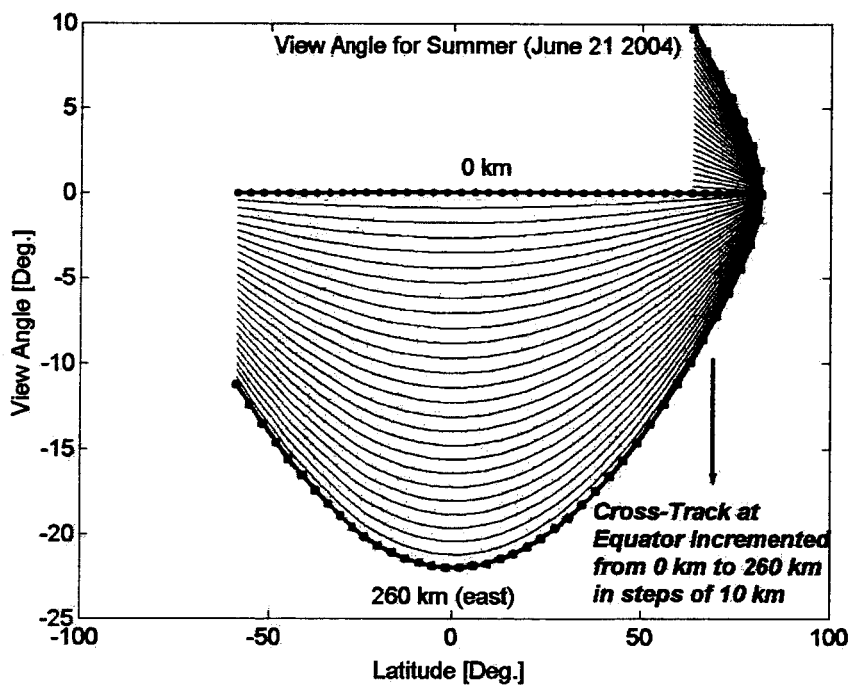


Figure 9. MODIS Pixel View Angle for Different Eastern Cross-track Shift Ranging from 0 to 260 km in Steps of 10 km versus Latitude

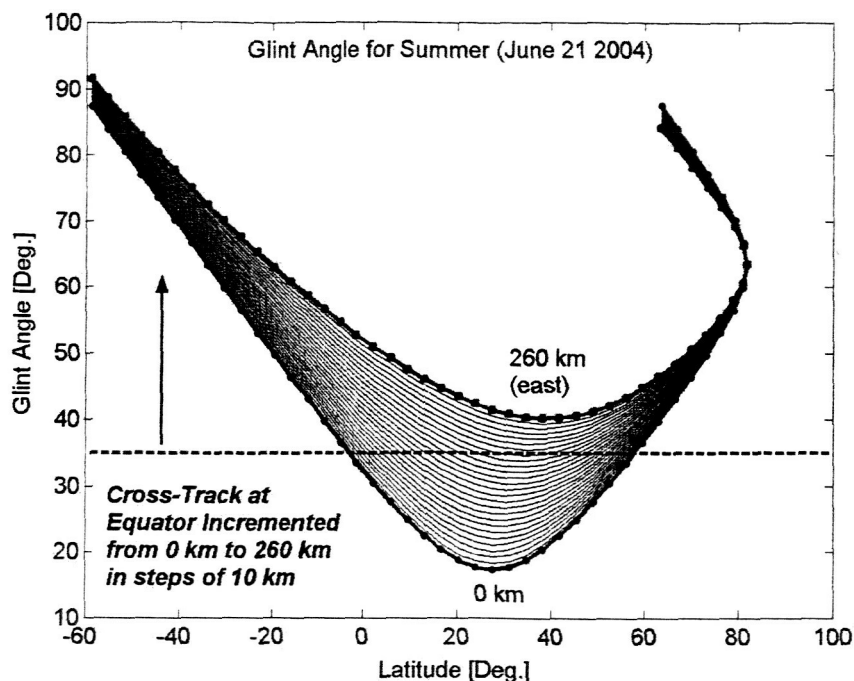


Figure 10. Sun Glint Angle for Different Eastern Cross-track Shift Ranging from 0 to 260 km in Steps of 10 km Versus Latitude at the Summer Solstice

To guarantee a minimum of 35° sun-glint angle for the first two years of CALIPSO's mission, a nominal cross-track shift of 217.5 km with respect to the Aqua reference path (i.e., World Reference System- 2) is required.^{12,13} However, due to a solar array power loss concern, a nominal cross-track shift of 215 km with respect to the WRS-2 grid was used. Once the nominal cross-track was determined, the effect of the worst-case launch error budget (see Table 1) on the sun-glint angle was examined for four epochs: the spring equinox (March 21st), the worst case (close to summer solstice on June 21st), the fall equinox (September 22nd) and the winter solstice (December 21st).

Figure 11 shows the nominal CALIPSO view angle evolution as a function of Aqua's latitude (center curve). It also depicts the effects of the maximum cross-track error on the view angle (top and bottom curves).¹¹ Although this figure shows data for the spring equinox, the results apply to any date in the year as the view angle history depends mainly on the formation flying design and not on the epoch.

Finally, Figure 12 summarizes the minimum sun-glint angle as a function of the maximum view angle for all the considered cases. The four curves depict the view angle evolution as a function of time of year; the bottom curve is for the worst case date in 2006 (close to the summer solstice). The center data point of each curve represents the nominal CALIPSO sun-glint angle; over the course of the year. During its first phase, Calipso nominal sun-glint angle reaches an absolute minimum of 34.85° and its nominal view angle reaches a maximum of 17.125° . A cross-track error of +15 km causes a minimum glint angle of 35.945° and a maximum view angle of 18.19° . Only the -15 km cross-track error case violates the minimum sun-glint angle constraint with a minimum of 33.715° glint angle and a maximum view angle of about 16.04° .

However, the CALIPSO initial conditions could be determined by positioning it on the eastern side of its maintenance window during the worst summer year.

Table 1
CALIPSO CROSS-TRACK ERROR BUDGET RELATIVE TO AQUA¹⁴

<u>Error Source</u>	<u>Error (km)</u>	<u>Comments</u>
Launch Vehicle Inclination Errors	0.0	Correct with Delta-V maneuvers
Launch Errors Total (RSS)	±3.3	Includes a ±2.2 km for the line-of-nodes error (±0.02°) and ±2.5 km for the launch window error
Aqua's Cross-Track Error	n/a	±10 km already included in the analysis (ephemeris)
CALIPSO's Cross-Track Error	±10.0	±21.5 second control box
Orbit precession at insertion orbit. Assumes stay in insertion orbit for 45 days to phase with Aqua spacecraft.	0.0	See Mission Analysis for Jason TP2-NT-J0-382-CNES
Margin	±2.0	
Total	±15.3	

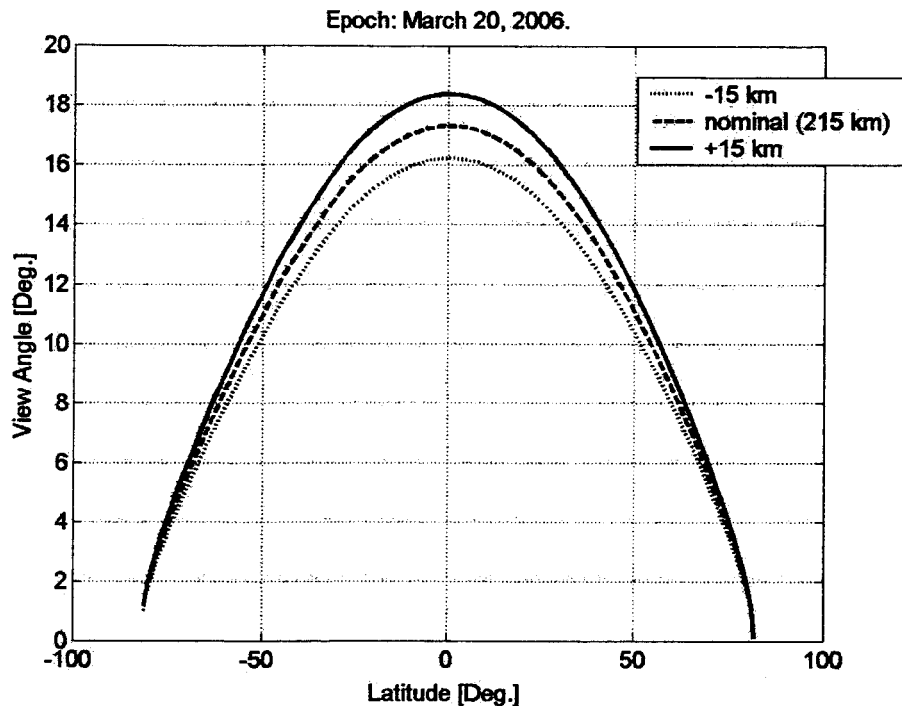


Figure 11. Calipso View Angle (Absolute Value) as a function of Latitude at the Spring Equinox

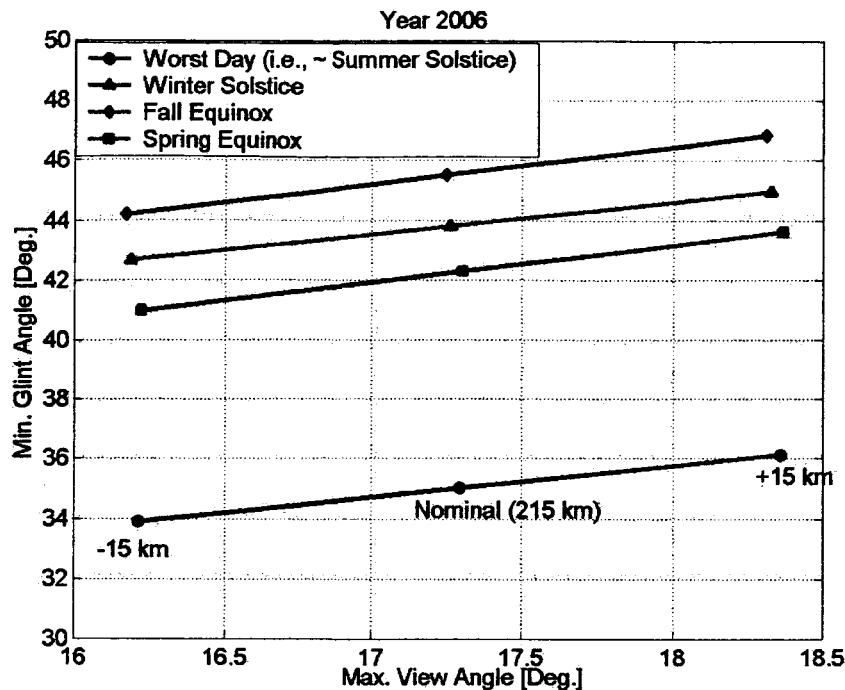


Figure 12 Minimum Glint Angle vs. Maximum View Angle for the Nominal CALIPSO Orbit with Added Cross-track Error

NOMINAL SUN GLINT AVOIDANCE FORMATION FLYING LIFETIME ANALYSIS

In the previous section, we determined the nominal cross-track shift with respect to Aqua so that CALIPSO does not perform coincident imaging with any portion of the MODIS swath suffering from sun-glint. In this section, we compare the new formation flying strategy to the original formation flying strategy where CALIPSO flew the same ground track as Aqua.¹⁵ The comparison was made for two specific parameters: beta angle and overall delta-V budget. The beta angle must be closely monitored to ensure CALIPSO power margins are maintained. Another parameter considered was the overall delta-V budget. For the new formation flying strategy, CALIPSO is shifted 215 km east of Aqua sub-satellite point. Phase 2 of the mission requires the spacecraft to precess through the entire western edge of the MODIS swath. As a result, the delta-V budget must increase in order to accommodate a larger inclination maneuver as compared to the initial strategy. Note that the separation time at equator crossing remains unchanged between the two strategies at a nominal value of 1.22 minutes (center-to-center of Aqua and CALIPSO ground-track control boxes). This value assumes that both Aqua and CALIPSO maintain a ± 10 km control box. For the sun-glint avoidance formation flying strategy, the spacecraft will be maintained to a WRS-2 grid shifted 215 km east during Phase 1. During Phase 2, both formation flying strategies will maintain a control box with respect to a WRS-2 drifting with the spacecraft plane.

CALIPSO is required to follow Aqua by up to 2 minutes and 45 seconds for coincident imaging to occur. For the CALIPSO and Aqua formation, only CALIPSO is required to perform maneuvers to control the formation. Aqua simply maintains its own mission requirements, maneuvering as needed. Table 2 summarizes the initial formation flying (Formation 1) and the

new sun-glint avoidance formation flying (Formation 2) requirements for each phase of the mission.

Table 2

FORMATION FLYING REQUIREMENTS FOR FORMATION 1 AND FORMATION 2

	<u>Nominal Separation Time at Equator Crossing¹</u>	<u>Cross-Track Separation with respect to Aqua at Equator Crossing</u>	<u>Phase Duration</u>	<u>Control Box Grid Reference</u>	<u>Control Box Size</u>
Phase 1					
Formation 1	1.22 min	0 km	2 years	WRS-2 Grid	± 10 km
Formation 2	1.22 min	+ 215 km	2 years	WRS-2 Grid + 215 km shift	± 10 km
Phase 2					
Formation 1	1.22 min	drift from 0 km to - 1165 km	1 year	n/a	± 10 km
Formation 2	1.22 min	drift from +215 to -1165 km	1 year	n/a	± 10 km

¹ This nominal separation time assumes that both CALIPSO and Aqua maintain a +/- 10 km control box.

Figure 13 illustrates CALIPSO's location relative to the swath of the Aqua MODIS instrument for both the Formation 1 and Formation 2 scenarios. For Formation 2, CALIPSO remains at 215 km east of the MODIS swath during Phase 1 and it will sweep from 215 km east of Aqua sub-satellite through the entire western side of the MODIS swath during Phase 2.

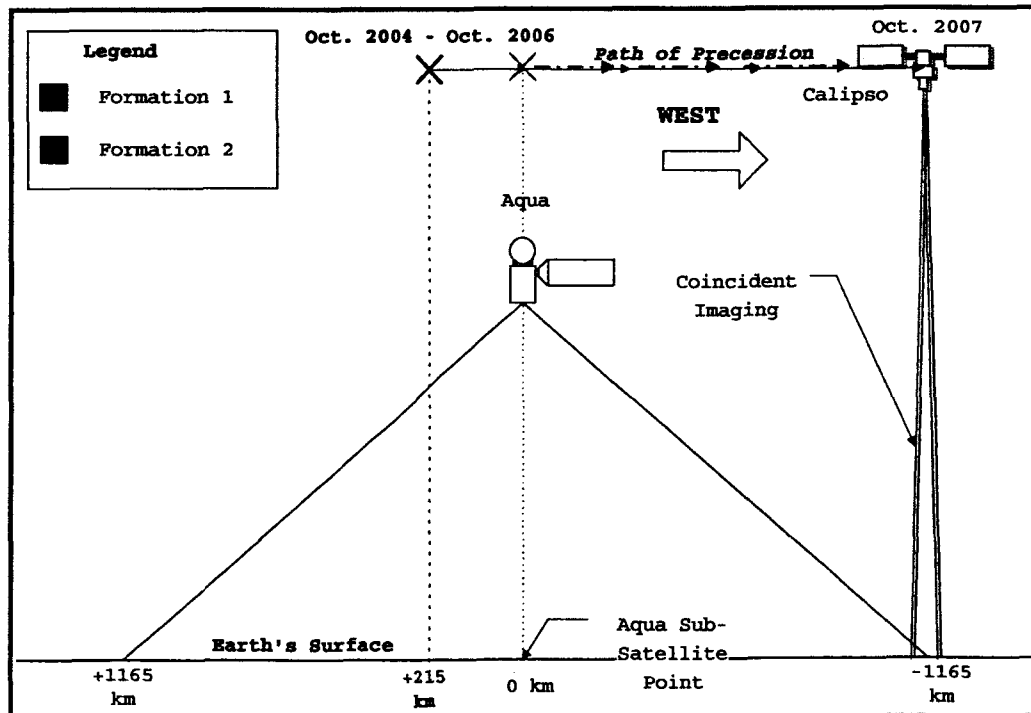


Figure 13. CALIPSO in the Aqua MODIS Swath for Formation 1 and Formation 2 (not to scale)

For each formation scenario, CALIPSO's right ascension of the ascending node and mean anomaly are initialized to satisfy the requirements identified in Table 2. Aqua and CALIPSO will then perform their ground-track control maneuvers independently of one another to maintain their respective control boxes. This independent control box strategy will maintain the separation time within 1 minute 13 seconds \pm 21.5 seconds (see Figure 14).¹⁻⁶

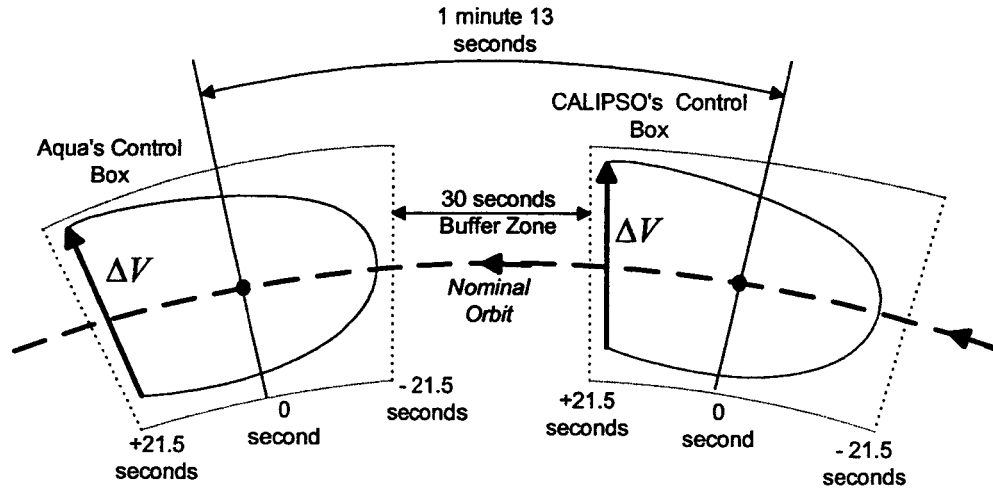


Figure 14. Schematic of the Aqua and CALIPSO Ground-Track Control Box and Time Separation

This setting implies that the lag time has to be adjusted to the actual positions of Aqua and CALIPSO in their respective boxes at the starting epoch of the run. The initial position of CALIPSO in the control box is arbitrarily chosen close to Aqua's for this analysis. However, it is planned that CALIPSO will be positioned in the center of its control box with respect to Aqua at the end of its ascent phase. This is not taken into account in this analysis since the ascent phase is not included and the simulation starts directly with the operational parameters.^{4,5,16} The CALIPSO formation flying control depends solely on a ground-track error control scheme. The ground-track error control is fully automated using the FreeFlyer[®] targeter. Note that for Formation 2, CALIPSO is controlled to a customized WRS-2 grid shifted 215 km east. Phase 2 of the CALIPSO mission is initiated with an inclination maneuver. The CALIPSO inclination is chosen to produce the desired precession across the western portion of the MODIS swath for the last year of the mission. The chosen inclination will determine the rate of change of the mean local time, and therefore the position with respect to the MODIS swath throughout the remainder of the mission. The MODIS swath is nominally 2,330 km wide, centered at Aqua's sub-satellite point. For the Formation 1 scenario, CALIPSO should nominally start and end at 0 km and -1165 km, respectively, in cross-track distance from the Aqua sub-satellite point as illustrated in Figure 12. For the Formation 2 scenario, CALIPSO should nominally start and end at +215 km and -1165 km, respectively. During the precession phase, CALIPSO mean local time starts at 13:33:00 and ends at 12:54:00 for Formation 1 and starts at 13:40:48 and ends at 12:56:24 for Formation 2. As explained previously, when CALIPSO performs an inclination maneuver to precess through half of the MODIS swath, its orbit becomes quasi-Sunsynchronous and the frozen condition no longer holds. For this section, the CALIPSO formation flying scheme was chosen to be controlled to a drifting WRS-2 grid with a drift rate equal to CALIPSO's orbit plane drift relative to Aqua's orbit plane.

Overall, the CALIPSO-Formation 2 strategy requires a delta-V budget about 4 m/s higher (9% increase) than the CALIPSO-Formation 1 strategy. Table 3 summarizes the delta-V budgets for both strategies. The Formation 1 and 2 strategies have a similar control delta-V budget. Indeed, there is no fundamental difference in their control strategies. For Phase 1, the Formation 1 strategy maintains a ± 10 km error with respect to the WRS-2 grid. Similarly, the Formation 2 strategy maintains a ± 10 km error with respect to a WRS-2 grid shifted 215 km to the east. As expected, the major contributor to the delta-V budget increase is the inclination maneuver to begin Phase 2 of the mission. The Formation 2 strategy requires a larger maneuver to reach the end of Aqua-MODIS swath as compared to the Formation 1 strategy because of the initial bias of 215 km. The Phase 2 control strategies are identical.

Table 3
OVERALL DELTA-V BUDGET COMPARISON
(FORMATION 1 (0 KM) VS. FORMATION 2 (215 KM))

Formation Flying Strategy	Inc Delta-V (m/s)	GTC (m/s)	SepC (m/s)	Total (m/s)
Formation 1 (0 km shift)	31.18	0.50807	0.2301	31.92
Formation 2 (215 km shift)	35.20	0.50842	0.2352	35.94
difference	+ 4.02	+ 0.00035	+ 0.005	+ 4.02

Figure 15 shows the evolution of the difference in beta angle between the two formations. For Phase 1 of the mission this difference fluctuates about the nominal value of 1.9314° . During Phase 2 the difference decreases as both spacecraft formation drift towards the same target at the western end of the Aqua MODIS swath.

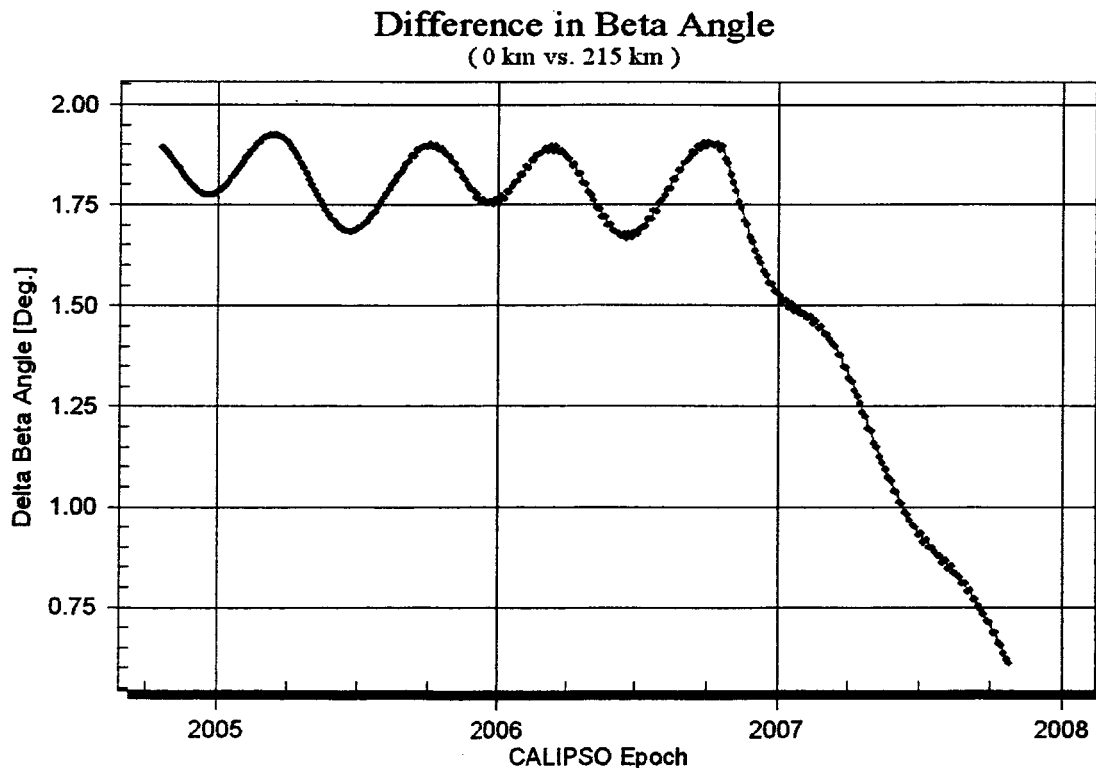


Figure 15. Difference in Beta Angle Between Formation 1 and Formation 2

CONCLUSIONS

CALIPSO will fly in formation with the Aqua spacecraft to obtain a coincident image of a portion of the Aqua/MODIS swath. Since MODIS pixels (defined as portions of the MODIS swath that are the same width as the CALIOP beam width) suffering sun-glint degradation are not processed, it is essential that CALIPSO only co-image the glint free portion of the MODIS instrument swath. This paper presented the results of the CALIPSO mission sun-glint avoidance strategies. Once defined, the sun-glint geometry was implemented in a FreeFlyer[®] script. A trade-space study was performed which varied CALIPSO's eastern cross-track shift with respect to Aqua's at the equator crossing from 0 km to 260 km in steps of 10 km. A minimum cross-track shift needed to avoid coincident imaging of a portion of the MODIS swath affected by sun-glint was found with this initial parametric scan and then was refined to within 1 km accuracy. A nominal cross-track shift of 215 km with respect to the WRS-2 reference path was found so as to ensure that CALIPSO will not suffer any loss of data due to sun-glint. Once the nominal cross-track was obtained, the new CALIPSO operational state was determined for the current launch date with a nominal lag time of 1.22 minutes. The impact of the cross-track error budget on the sun-glint analysis was also examined. Finally, we compared the new formation flying strategy to the original formation flying strategy where CALIPSO was to fly the same ground track as Aqua. The comparison was made for two specific parameters: beta angle and overall delta-V budget. We found that if CALIPSO flies a sun-glint avoidance formation flying strategy, it will suffer an increase of about 9% in overall delta-V expenditure and will on average fly a 1.9314° increase in the beta angle for the first two years of the mission.

ACRONYMS

CALIPSO	- Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations
LaRC	- NASA Langley Research Center
CNES	- Centre National D'Etudes Spatiales
HU	- Hampton University
IPSL	- Institute Pierre Simon Laplace
CALIOP	- Cloud-Aerosol Lidar with Orthogonal Polarization
MODIS	- MODerate resolution Imaging Spectro-radiometer
WRS-2	- World Reference System-2

ACKNOWLEDGEMENT

This work has been supported by NASA Goddard Space Flight Center (GSFC) under contract NAS5-01090. The authors would like to thank the Task Monitor at GSFC, Mr. Osvaldo Cuevas, and the Task Manager at a.i. solutions Inc., Mr. Jeff Dibble.

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